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Making "The Mechanical Universe"

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"The Mechanical Universe and Beyond" is an introductory college-level physics telecourse, including calculus, made for broadcast television and classroom use. This article describes the inception and history of the project and the techniques and strategies that were used in producing it. A project to adapt the series for use in high schools is also discussed.

I. INTRODUCTION

On 30 January 1983, the pilot program of The Mechanical Universe series, "The Law of Falling Bodies," was formally unveiled before an audience consisting of the project's National Advisory Committee, the president of Caltech, high-ranking representatives of the sponsoring Annenberg/CPB Project, and various other luminaries. After months spent on that single program, producer Peter Buffa had worked through the previous night to finish postproduction editing, and arrived at the 10:00 a.m. showing, precious tape in hand, with less than 10 min to spare. It was a moment of high drama, characteristic of the television industry, but much less familiar in the halls of higher education.

The showing was successful. Having passed this critical test, the project went on to produce a total of 52 television programs and 3 volumes of textbooks,[1] plus teacher's manuals, study guides, and more,[2] all designed for use in college-level courses, as well as a complete set of videos and print materials adapted for use in high schools.[3] The project lasted more than five additional years, and cost nearly \$10 million. The Mechanical Universe is the physics entry in the rapidly developing activity of televised higher education.

In the fall of 1986, telecourses broadcast on public television stations had an estimated audience of 2 360 000 households (out of a potential 87 000 000).[4] Furthermore, network television is by no means the only way telecourses can reach their audiences. A January 1987 Roper poll indicated that 47% of American households own VCRs, and 50% are connected to cable television outlets (93% own color television sets). In the 1984–1985 academic year, some 902 college-level institutions (32%) offered telecourses to students, and 87% of all public, four-year institutions used video for in-class instruction.[5] Like it or not, television has become an indispensable part of American higher education. Television in higher education is part of a quiet revolution that has seen the traditional college student (18–22 years old, enrolled full time) become part of a tiny minority (less than 20%) of those enrolled in college credit courses.

Physics is not a newcomer to televised education. The first televised physics lecture dates back to the 1930s. A remarkable number of today's American research physicists—particularly those from rural and poorer sections of the country—trace their interest in the subject to the early morning physics classes offered on Continental Classroom in the 1960s. The Mechanical Universe follows in that tradition, and benefits from the improved production quality that has characterized the evolution of American educational television. Nevertheless, making The Mechanical Universe posed some formidable challenges.

The essence of the problems faced by the designers and producers of The Mechanical Universe (hereafter referred to as TMU) was expressed in the heat of battle (so to speak) in a letter from David Goodstein to Dr. Mara Mayor, Director of the Annenberg/CPB Project, dated March 1985, on the occasion of one of the many crises the project had to survive:

> "Intellectually, technically and philosophically, physics and television are two separate cultures with almost no bridges between them. Working together with unfailing mutual cooperation, admiration and respect, it is nevertheless an impressively time-consuming and arduous task to span that gap well enough to produce television programs. To put this point more succinctly, there is no one here on the Caltech side who is capable of reading, much less writing, a television script competently. Conversely, there is no one on the production side who knows enough about physics even to begin to plan an important sequence, much less write a script or produce a program. This situation is a symptom of the malady of science illiteracy that *The Mechanical Universe* is intended to help cure..."

To make matters more difficult, unlike previous telecourses, TMU was being made by an academic institution, which had the final say on its content. The letter continues a bit later on:

> "Let me be more explicit about the differences between a conventional telecourse and *The Mechanical Universe.* In the conventional course, the production company begins by convening a panel of hired academic consultants. These experts put together an outline of "learning objectives," choose a textbook, suggest real-world examples or settings that might be used, name experts (often themselves) to be interviewed on camera, and so on. Within this context, the chosen authorities are interviewed, accumulating inexpensive footage that can be sprinkled as needed through the series. Then scripts are written by scriptwriters whose general characteristics are that they are young, eager to work, not yet members of the writer's guild, and, of course, have no academic qualifications in the subject being taught. The basic ele-

ments of the programs are interviews and cover footage with voice-over narration, and an absolute minimum of expensive original footage. In post production, these programs are assembled by a purely mechanical procedure of laying in scenes from master reels by predetermined numbers, with simple cuts between scenes."

There are, of course, exceptions to each of these generalizations. For example, some previous telecourses have commissioned textbooks of their own, some scriptwriters are not so young and inexperienced, and so on. Nevertheless, the general description is quite accurate. The letter goes on:

"Courses that are made in that way are basically education by committee, with the crucial job of teaching mainly in the hands of the scriptwriters and producers. But the whole idea of college education is to give students the benefit of learning from people who have spent a lifetime mastering their subjects and, if possible, adding new knowledge to them. The expert interview doesn't serve that purpose adequately. The crucial part is organizing a subject and seeing the connections between its parts, precisely what telecourses entrust to scriptwriters."

"*The Mechanical Universe*, by contrast, arises out of a real physics course at a real—and excellent—university. It represents a single, unified vision of what physics is about, and how it's connected to its roots in mathematics, history and society. Under those circumstances, new techniques for educational televison had to be invented."

"The basic devices are extensive and brilliant computer animation by Jim Blinn, a fully qualified member of the academic staff (Dr. Blinn teaches at Caltech among other things); historical recreations of exquisite authenticity as well as color and interest; "concept locations," i.e., sites more or less relevant to the subject of each program where background footage can be accumulated; sparkling, ingenious narration written by story editor Jack Arnold and his writers; and brief bookend segments in a real lecture hall with (mostly) real students, where things can be said that can't quite be put into the mouth of our affable, faceless narrator."[6]

Had that letter been written from a balanced point of view, it might have added that working with academics who were more than mere advisors was a novel and not always pleasant experience for the production staff, that the writers could not be blamed for not having academic credentials, and that they and the other members of the production team often performed heroically, both on this series and on previous ones.

II. HISTORY OF THE PROJECT

The Mechanical Universe project had its roots in a routine revision of Caltech's introductory physics courses, which was assigned to Goodstein and begun in 1979. It was the first major change in those courses since they had been taught by Richard Feynman in the early 1960s. When, in 1981, the revision had been accomplished, the question was: How would the new approach be preserved for the benefit of subsequent Caltech students?

The idea arose of resorting to television, which seemed likely at the time to be less work than the alternative of writing another textbook. With the perfection and diffusion of technologies such as home videotape, cable distribution, and so on, it also seemed likely that television would play a significant role in the future of education, and this occasion offered an opportunity to explore the possibilities.

The project began with seed money that the Weingarten Foundation had placed at the discretion of Caltech's president, Dr. Marvin Goldberger. Under Goodstein's direction, Don Delson, a Caltech employee with a background in broadcasting, became project manager and began investigating the possibilities of educational television. He made contacts at the local PBS station, KCET in Los Angeles and, through them, with Sally Beaty, president of The Southern California Consortium and The Corporation for Community College Television (CCCT), entities that, respectively, use and produce college-level television courses.

In the fall of 1981, as discussions began about the possibility of Caltech, CCCT, and KCET collaborating on a physics television course, Walter Annenberg, publisher and former ambassador to Great Britain announced a gift of \$10 million per year for 15 years to support the use of telecommunications in higher education. The Annenberg gift is administered through the Corporation for Public Broadcasting (CPB), a quasiprivate corporation set up to act as a buffer between the Congress, which appropriates about \$200 million per year for public broadcasting, and the stations of the Public Broadcasting System (PBS), which spend the money. The Annenberg CPB Project is a separate unit within CPB, with its own staff, and its own external, decision-making council. The money is channeled through the Annenberg School of Communications at the University of Pennsylvania. In February 1982, TMU was one of six projects chosen for funding (out of about 250 proposals) in the first round of Annenberg awards.

The financial and administrative history of TMU is a complex and sometimes painful subject. For example, KCET was quietly dropped from the collaboration on the day the award was made, when the Annenberg/CPB staff determined that the project could be produced at much lower cost without their participation. The original award was for \$1 million, with Caltech responsible for raising a matching amount to fund the \$2 million budget for 26 programs. By November of 1982, it had become clear that matching funds would not be raised. The Annenberg stamp was too clearly evident for corporate or other foundation sponsors to be interested, and the amount was too large for most other donors. In November of 1982, without being asked to do so by Caltech, the Annenberg/CPB Council generously changed its mind, and funded the full \$2 million.

In spite of this generosity, there were serious financial difficulties that would not be cured until much later in the project's history. The causes of these problems are easy to understand in retrospect. For one thing, Annenberg/CPB, in making the initial award, imposed a requirement that the pilot program be made and evaluated as a condition for completion of funding. The pilot program (The Law of Falling Bodies) proved to be a valuable part of the learning process for everyone involved, but it was also extremely expensive in both time and money (it took many months and more than \$300 000 to produce) and no special budget had been set aside for it. Second, the original production budgets for the series were based on CCCT's experience with previous telecourses, which had used relatively inexpensive production techniques. Caltech (i.e., Goodstein), with no television experience at all aside from the opulent pilot program, designed programs and made decisions that led to far higher costs.

In November 1983, a new proposal was funded to expand the project to 60 programs, two semesters instead of one, with a total budget of \$4.9 million. This was done because the first 26 programs (covering mechanics and calculus) would not constitute a complete course, because the early programs were judged very successful, and the team that made them would never be reassembled if the first part were finished before a follow-on was in place, and finally because the financial difficulties had begun to be visible and it was felt that they would be less serious if subsumed in a larger project.

This last piece of reasoning (by Goodstein) is similar to that of the merchant who loses money on every item, but makes up for it by large volume. To be sure, the larger project made it easier to absorb the cost of the pilot, but each program was still costing more—and taking longer—than had been budgeted. This fact became clear in February 1985. By then, enough programs had been completed (12) to allow a realistic cost analysis. The conclusion was devastating: With the first 30 programs due to go on the air in a matter of months, TMU could not meet either its budget or its schedule.

In the negotiations that took place after Goodstein notified the Annenberg/CPB office of these conclusions, Mara Mayor and Dr. Hyman Field, Senior Project Officer, made it clear that they wanted programs of the quality they were receiving, not lesser productions that could be made at lower cost. As a result, a new arrangement was worked out, with the series redesigned to encompass only 52 programs,[7] and the budget increased to \$5.8 million. With these changes, TMU seemed at last to have a realistic schedule and realistic budget. Unfortunately, one nasty shock still remained. Rather than getting the needed cash flowing quickly, CPB, employing a tactic familiar to everyone in the public broadcasting sector, delayed writing the contract amendment so long that the advantages of the new agreement were nearly undone. Nevertheless, the full series of 52 programs was first broadcast during the academic year 1986–1987, as scheduled.

Even before TMU had its first million dollars, work began assembling the principal participants. Delson's inquiries about sources of animation quickly turned up Dr. James Blinn, a leader in the field of computer animation, working at Caltech's Jet Propulsion Laboratory. An ad in *Physics Today* for a one-year not-yet-funded position as associate project director brought in about 40 excellent applications, from which Dr. Richard Olenick of The University of Dallas was chosen. In the meantime, Sally Beaty, who would serve as Executive Producer of the series, enlisted seasoned educational television producer Peter Buffa to head the production side of the project. Buffa put together a staff that included, most notably, Associate Producer, Mark Rothschild, Story Editor, Jack Arnold, and Production Coordinator, Robert Lattanzio. The academic side was fleshed out with Professor Steven Frautschi of Caltech's Physics faculty and Professor Tom Apostol of Mathematics. Apostol, well known for his highly regarded textbooks, joined the project after Goodstein outlined his plans to a meeting of the faculty of Caltech's Division of Physics, Mathematics, and Astronomy early in 1982. Apostol feared, probably with good reason, the treatment that mathematics might receive in the series if a mathematician didn't participate. Other members of the academic staff included Professor Robert Westman of UCLA and Dr. Judith Goodstein of Caltech, both Historians of Science, and Science Educator Dr. Dave Campbell of Saddleback Community College.

As is fitting for a project of this scope, a National Advisory Committee was formed.[8] It met in Pasadena twice in the course of the project's evolution. There was also a local advisory committee[9] that met far more often and a Caltech Oversight Committee. This latter committee, appointed at the direction of Caltech Provost Jack Roberts, had the task of assuring that the Institute would not be embarrassed by what TMU put on little screens all over the country. It dissolved itself after reviewing the first half-dozen programs on the grounds that it was not needed.

III. PRODUCTION

The raw material for TMU—both the television programs and the textbooks—was a set of verbatim transcripts of the lectures delivered by Goodstein in the revised Caltech physics course. It was decided at the outset, however, that the material would be presented at two levels, at least in the textbooks if not in the television programs. The upper level, suitable, e.g., for physics and engineering majors, corresponds to the original Caltech course (and has been adopted at Caltech). The other textbook, which corresponds to the level of the television programs, was intended for a more general audience. Nevertheless, it was decided that it should include differential and integral calculus. These subjects would be presented—as they had arisen historically—as part of the science of mechanics. Mastering the relatively simple techniques of calculating derivatives and integrals would make physics easier to understand than using the pseudocalculus employed in many college physics courses.

After the first round of adoptions of the mechanics portion of the series in the fall of 1985, an extensive telephone survey of users was undertaken by the Annenberg/CPB Project, in order, among other objectives, to test whether this strategy had been successful. The results were surprising. Liberal Arts students had little difficulty learning calculus. In the words of the consultant who had conducted the survey, this was a "major pedagogic triumph" of the series. He did uncover an important problem, however: Although algebra was not a problem for most students, they did have severe problems due to inadequate preparation in trigonometry. A trigonometry primer, written by Apostol,[2] was quickly added to the project's arsenal of aids to students and teachers.

As the project began to evolve, each academic player undertook specific responsibilities. For example, Olenick (who would later direct the high-school adaptation of the television material) wrote first drafts of most chapters of the lower level textbook. These were augmented and revised by Apostol and Goodstein. Frautschi was the lead author in transforming the lower level text to an advanced edition. Apostol had primary responsibility for all mathematical portions of both textbooks and scripts. On the production side, once a script was in hand, a well-oiled machinery would go into action, planning "shoots," many at remote locations, turning up stills and stock footage, and so on. The camera crew (Pat Allen, camera and lighting, George Stupar, sound and everything else) was hired for each day's shooting.

The lecture hall sequences were shot in blocks, two programs per day, two or three days per week, during the summers of 1983 (for TMU) and 1985 (for Beyond TMU). In each case, this was before most of the scripts had even been begun, much less finished, and so the scripts had to conform to the already shot bookend sequences. The material in the scenes was all taken from real Caltech lectures, and the scenes were shot without scripts because Producer Buffa wanted a sense of realism and spontaneity. However, since each shot was repeated five or more times, spontaneity sometimes suffered.

The scenes were shot before an audience of about 20 extras, whose entrances and exits were carefully choreographed and rehearsed. The production staff felt they were combining the best parts of the then hit series *Paper Chase* and *Hill Street Blues*. In fact, after searching futilely for a classroom that resembled the one in *Paper Chase*, Buffa reluctantly settled for the real one used by Caltech physics classes, but not before installing fake wood paneling. In a classic case of life imitating art, the Physics Department was so impressed by the result that it actually installed similar panels. Audience reaction shots of real Caltech students were sprinkled in later during postproduction editing.

As mentioned in the letter quoted earlier, the most difficult production problem was scriptwriting. In the early going, Story Editor Jack Arnold organized a string of freelance writers to whom he assigned scripts. Later, writer Don Button was hired full time, and most scripts were written in-house. Early in the project, the writer of a given script would be given edited portions of relevant lecture transcripts to work with, supplemented by long, earnest discussions in which the academic staff would seek to teach him or her the necessary physics. Later on, a new procedure was adopted. The writers were given drafts of all the physics scenes, written in advance. Their task was thus to weave a program between the bookends and around the physics scenes.

Each script would start with the choice of a "concept location" (e.g., a magician's performance for "Static Electricity," a gas station in the desert for "Temperature and the Gas Law," and so on. Some programs were purely historical in theme and did not have a location in this sense). With this starting point, the writer would successively submit (for Caltech approval) a one-page outline (the "concept"), a multipage, detailed prose description (the "treatment"), and, finally, a draft script. At this point, the script was "polished" by Arnold, who rewrote the narration into what became a distinctive TMU style, and the result was reviewed once again by the academic staff and sometimes by outside consultants to check for accuracy. If it passed this test, it was declared "in production" and the production team would be free to start planning scenes. Of course, in reality the process seldom worked this smoothly, and, as we'll see below, every script underwent extensive further rewriting at later stages.

The scriptwriting process was the principal stage for a classic conflict between the academic and production sides of the project. In succinct but exaggerated terms, the production people were in favor of fewer equations and more "beauty shots," the academics wanted more physics and less time wasted on filler material. The outcome of the fray may have been influenced by the fact that the final decision was in the hands of the academics. However, it was much more strongly influenced by the fact that each side had genuine respect for the professional competence of the other, each understood that the ongoing debate itself was healthy so long as it remained in reasonable balance, and perhaps by the fact that, with separate offices in Pasadena and (naturally) Hollywood, the two sides did not meet often enough to get on each other's nerves.

Lurking behind that debate, however, was a deeper question: For what audience was TMU intended?

Formally, according to the charter of the sponsor, the primary audience was to be the "nontraditional student," especially "distance learners," earning college credit by watching television. In reality, of course, physics is far too difficult to learn merely by watching television, but it was hoped that with a resourceful, dedicated local teacher, a physics course by television would be possible, and that the teaching of introductory physics at any level could be enriched using these programs in or out of the classroom. It was also hoped that a large, casual, nonstudent audience would watch the programs for pleasure and instruction. In making specific decisions, however, it's often useful to have a clearer target in mind. For TMU, that ideal target audience was the high-school physics teacher. We shall return to this point later.

The Mechanical Universe, from beginning to end, is intensely historical in its approach to physics. This orientation is a direct reflection of the Caltech course from which it arose. In essence, the earlier Feynman course had sought to make physics exciting by relating each subject, wherever possible, to contemporary scientific problems. The new course took the opposite tack, of trying to recreate the historical excitement of the original discovery. For example, classical mechanics—a notoriously difficult and uninspiring subject for students—is treated as the discovery of "our place in the universe." Accordingly, celestial mechanics is the backbone of the subject and its climax is Newton's solution of the Kepler problem.

Given this point of view, and the central imperative of television—that there must be something on the screen, preferably moving, at all times—historical recreations inevitably became a staple part of the project.

The historical scenes in TMU are generic in nature. Young Newton strolls through an apple orchard, old Newton testily refuses a cup of tea from a servant, and so on. To have tried to recreate a specific moment or event (Newton inspired by the apple falling) would have been silly and presumptuous (and expensive). The scenes that were made could be used in many programs, whenever the person in question came up in the narration. Aside from Newton, scenes were made of Galileo, Leibnitz, Benjamin Franklin, Michael Faraday, and James Clerk Maxwell. In addition, about 11 min of Kepler footage was purchased from an earlier PBS series, *Cosmos*. To film these scenes and others, crews were sent to England, Holland, and Italy as well as Dearborn and Philadelphia, but young Newton's apple orchard was in Yucaipa, California, Galileo confronted Vatican authorities at the Clark Library in South Central Los Angeles, and Leibnitz's visit to a German royal court unfolded in the main lounge of The Athenaeum, Caltech's faculty club. For more recent personages (Einstein, Michelson, Rutherford), stock footage, some of it rare archival material, was turned up. But Robert A. Millikan posed a special problem.

Early in the series, a program is devoted to Millikan's oil-drop experiment, partly as an application of Newton's second law, and partly to introduce some philosophical ideas about how science is really done. To make this program, some sort of Millikan footage was needed, but an actor playing Millikan did not seem to be a good idea, especially at Caltech where many people still remember him well. The solution was to create a meticulously detailed "Millikan Museum," combining elements of his laboratory and his office, in a room in the Norman Bridge Laboratory where he had worked. The set involved thousands of artifacts, many of them Millikan's own (the iron canister of the oil-drop experiment, his desk, his letters, papers, and notebooks, etc.). After three days of shooting the scene under the supervision of Associate Producer Mark Rothschild, the museum was disassembled, to live on only on videotape.

In addition to all the above, the series includes a large selection of stills (usually shot with a moving camera), many of them portraits or pages from rare first editions of important books. These were generally dug up by researcher Carol Bugé. Extensive use was also made of stock footage, much of it taken from series previously produced by CCCT (*Oceanus*, *Project Universe*, etc.). There are also a small number of original cartoon (or cell) animations, executed by artist Mike Shaw.

The presentation of physics instruction in the series is done almost entirely by means of computer animation, which serves roughly the function of the blackboard in a classroom lecture. There are some 550 animated scenes in all, comprising about $7\frac{1}{2}$ h of screen time. To set the scale, consider that the commercial market rate for high-quality computer animation (the flying logos on television network broadcasts) is about \$4000/s. This work was done by Blinn, with help from his assistants, Sylvie Rueff and Tom Brown, at the JPL Computer Graphics Lab.[10] During the last 14 months of the project, Blinn turned out new animation at the astonishing rate of close to 3 min/week.

Blinn, whose undergraduate degree is in physics (his Ph.D. is in Computer Science), is one of those scientists who fell under the influence of Continental Classroom. The computer animated scenes in the "in-production" scripts seldom passed through his hands intact. In what ultimately became daily (7 days per week) consultation with Goodstein, the scenes were designed and developed to take maximum advantage of Blinn's vivid visual way of understanding physics, as well as the techniques at his disposal (many of them invented by him). A discussion of the visual, numerical, and other techniques used in animation for TMU is itself a book-length treatise.[11] We mention here only a few details in the hope of conveying some of the flavor of the enterprise.

Most of the scenes that will appear to casual viewers to be merely attractive illustrations, in fact use scientifically valid, sometimes very elaborate models. For example, the many scenes of atoms forming states of matter, solid, liquid, and interacting gas, are in fact two-dimensional molecular dynamics calculations, in which the "atoms," interacting via Lennard–Jones potentials, are given initial conditions and set free to obey Newton's laws (of course, it always took some experimenting with initial conditions to get the results to look right). Blinn used colors in a way that may have a subliminal effect, even if viewers don't notice his schemes explicitly. For example, differentiation makes quantities redder. Thus, position is green, velocity is yellow, and acceleration is red; angular momentum is pale blue and torque is lavender (blue + red). These are the colors of both the vectors and the algebraic symbols representing each quantity. In the program "Low Temperatures" there is a phase diagram in the pressure–temperature plane. Here, solid is earthy brown, liquid is watery blue, and gas is transparent white. Above the critical point, where there is no boundary between liquid and gas, the color shades smoothly from blue to white according to a formula based on the Van der Waals equation of state.

The problem of how to present detailed mathematical derivations is confronted, of course, in the animated scenes. The problem here is that one risks losing the audience either by skipping steps, or by presenting each step in an excessively didactic way. Skipping steps would rob the presentation of its rigor and continuity and leave the impression that there are things about physics that we consider too difficult or arcane to show to our audience. Going carefully through each step would have the same effect it often has in real lectures. In Buffa's memorable phrase, it would "put their brains into a 60-cycle hum." It would also be a woeful misuse of the television medium. The compromise solution of this problem, invented while designing the pilot program, is called the "algebraic ballet."

In an algebraic ballet, an animated derivation was done in detail, but rapidly and entertainingly. The viewer was not expected to absorb every detail merely by watching the symbols move on the screen.[12] But every step was displayed correctly and the mathematical argument was presented without losing the viewer's attention. Our own (strictly informal) evaluation of how well this works indicates a strongly age-related effect. Younger viewers—perhaps because they are more attuned to television, or possibly because they are not accustomed to understanding everything they see—seem to enjoy them much more than older viewers, who are made uncomfortable by the algebraic manipulations they cannot quite follow. In any case, the algebraic ballets do serve their primary function. Viewers are unanimous in agreeing that their attention is never lost during these mathematical passages.

Once Blinn finished animating each program, it was assigned to an editor to be assembled. The editor's job was to block out the program. He would read the narration onto the soundtrack of a $\frac{3}{4}$-in. tape, imitating the professional narrator's normal speed, then, using in-house editing equipment in the Hollywood offices, he would choose and transfer scenes onto the tape. The resulting reel, called a "rough cut," would be sent to Pasadena to give the academic staff its first clear picture of what had been created. The result was usually an intense period of rewriting under considerable time pressure, because the subsequent editing stages had to be scheduled in advance, and the final programs had to be delivered on a remorseless schedule that was tied to contract payments.

The first consideration was the animated scenes. Entirely new narration, timed to the actual scenes almost always had to be written. The second priority was the overall timing of the program. If it was more than 1 min long or short (almost always the case), serious emergency surgery had to be performed. Often, one or the other of these kinds of changes required work that affected every part of the original "production script." This rewriting was generally done by Buffa, Arnold, and Goodstein, with Apostol and others pitching in on some occasions. The program was then re-edited into a second rough cut that would be subject to detailed scrutiny by the entire academic staff. At this stage, however, changes were generally limited to the wording of narration, not to the order or length of scenes.

The final stages of preparation of each program involved recording narration by actor Aaron Fletcher, transfer by computer of the narration and scenes onto 1-in. broadcast tape, and the final video and audio editing, including sound effects, music (composed and synthesized for TMU by musicologists Sharon Smith and Herb Jimmerson), dissolves, and other special effects. These final stages, which cost close to \$20 000 per program, were done in the same rental facilities used by many commercial television programs. Mistakes were sometimes caught and corrected in this process, but each fix became progressively more difficult and expensive as the process unfolded. After a final check in Pasadena, the program was declared "in the can," and the can was sent off by overnight courier to the sponsor in Washington.

IV. HIGH-SCHOOL ADAPTATIONS

As remarked earlier, the ideal audience for TMU was high-school physics teachers. All of the participants in the project have come to be deeply impressed with the quality, dedication, and professionalism of the high-school physics teachers with whom we have been brought into contact, but those tend to be among the tiny minority who are genuinely well qualified to teach the subject. The lack of qualified high-school physics teachers in the United States is a notorious (and self-perpetuating) problem.[13] From the outset, combating that problem was seen as one of the central goals of the TMU project. To facilitate use of TMU for this purpose a new initiative was undertaken to adapt material from the programs for use in high-school classes. The idea was to induce teachers to study the college-level version so that they could use the high-school materials in the classroom with poise and confidence.

The high-school adaptations of TMU were begun during the summer of 1984. Under a materials development grant from the newly revived science and engineering education directorate of the NSF, 12 teachers were chosen from the many responses to an ad placed in *The Physics Teacher*.[14] They were convened for the first time in the summer of 1984 on the Caltech campus, under the direction of Olenick and Kathleen Martin, and have been at work ever since. The group is called the Materials Development Council (MDC).

Starting from scripts, rough cuts or, where available, final programs from the broadcast version, the MDC chooses topics suitable for presentation in high-school curricula and fashions from the available footage video modules, averaging 15 min in length, to be used in class. These are accompanied by extensive written materials for the teacher, including suggestions, background material, demonstrations, and sample questions to be used in conjunction with the videotapes. Each package is then field tested under professional direction[15] before being revised and issued for distribution. By the 1986–1987 school year, 70 teachers and thousands of students in 30 cities and 10 states were participating in the evaluations alone. Twenty-four modules have been completed, with four more planned.[16]

As originally conceived, TMU was to be "physics in a plain brown wrapper" for high-school teachers. "Crossover" teachers from other disciplines could brush up on their physics in the privacy of their own living rooms. In practice, this view proved to be naive. Teachers want and need special courses with considerable expert help, well-organized workshops, and, where possible, tuition and stipend support. Efforts to provide these services have been organized in a number of states.[17] Reports from the field indicate that teachers are willing to work very hard to improve their skills when given reasonable support, and that even those teachers who are well qualified in physics find new inspiration in the unusual approach and materials offered by TMU.

V. RESULTS

The diffusion and impact of TMU have been difficult to assess. One reason is that, although all PBS stations receive the programs via satellite, they do not have to pay for using them, and therefore do not have to report whether they have broadcast them. Nevertheless, it is known that in the fall of 1986 alone, TMU was carried by approximately 100 PBS stations and had an estimated casual audience in excess of 400 000 households. It has been purchased or licensed for use as a telecourse in more than 600 institutions of higher education and the high-school adaptations have been distributed to more than 2000 high schools in all 50 states. In addition, there have been numerous private reports of teachers at all levels taping broadcast programs at home for use in class, a procedure of noble purpose but questionable legality. Incidentally, neither Caltech nor CCCT receive any part of the revenues generated by distribution of the series.

An extensive formal evaluation of the pilot program[15] revealed a predominantly favorable response at all levels, but the evaluation was primarily designed to aid in making subsequent programs, rather than to judge the final utility of the series, and besides the results are difficult to assess because there is nothing with which to compare them. Anecdotal information in the form of letters and phone calls indicates very considerable enthusiasm among users at all levels from casual viewers to high-school students to research university professors, but there have also been a number of sharp disappointments, particularly when Instructional Television administrators have tried to handle TMU like a conventional telecourse. From a production point of view, the series has been very well received, winning an impressive string of awards at film festivals and competitions.[18]

A final judgment of the value of the project may be a long time in coming. Telecourses are generally broadcast at peculiar hours, but they are repeated many times. The "shelf life" of the project, both for broadcast and classroom use, is estimated to be approximately 10 years or more. A videodisk adaptation of the series, currently in production, could extend the life of the series into the next millennium.

[1]R. P. Olenick, T. M. Apostol, and D. L. Goodstein, *The Mechanical Universe: Introduction to Mechanics and Heat* (Cambridge U.P., New York, 1985); R. P. Olenick, T. M. Apostol, and D. L. Goodstein, *Beyond The Mechanical Universe: From Electricity to Modern Physics* (Cambridge U.P., New York, 1986); S. C. Frautschi, R. P. Olenick, T. M. Apostol, and D. L. Goodstein, *The Mechanical Universe: Mechanics*

and Heat, Advanced Edition (Cambridge U.P., New York, 1985).

[2]T. M. Apostol, D. A. Campbell, T. S. Dukes, and R. J. Sirko, *The Mechanical Universe: Trigonometry Primer and Student Study Notes* (Kendall/Hunt, Dubuque, 1986; Cambridge U.P., New York, 1988); D. A. Campbell, T. S. Kukes, and R. J. Sirko, *Beyond The Mechanical Universe: Student Study Notes* (Kendall/Hunt, Dubuque, 1986; Cambridge U.P., New York, 1988) and *The Mechanical Universe and Beyond Faculty Manuals* (PBS Adult Learning Service, Washington, D.C., 1986).

[3]The high-school adaptation is distributed by The Southern California Consortium, 5400 Orange Avenue, Suite 109, Cypress, CA 90630.

[4]Peter Dirr, Annenberg/CPB internal report, July 1987, unpublished.

[5]J. A. Riccobono, *Instructional Technology in Higher Education* (Corporation for Public Broadcasting, Washington, D. C., 1986).

[6]The narrator is faceless only to the uninitiated. The scripts were read by actor Aaron Fletcher, who also plays Galileo in the historical recreations. Some technical material is narrated by a female voice, actually that of Executive Producer Sally Beaty.

[7]The first 26 programs cover classical mechanics and calculus with special emphasis on celestial mechanics. The second 26 (Beyond The Mechanical Universe) cover electricity and magnetism, relativity, thermodynamics, and modern physics. The program titles are: Introduction to the Mechanical Universe; The Law of Falling Bodies; Derivatives; Inertia; Vectors; Newton's Laws; Integration; The Apple and the Moon; Moving in Circles; Fundamental Forces; Gravity, Electricity, Magnetism; The Millikan Experiment; Conservation of Energy; Potential Energy; Harmonic Motion; Conservation of Momentum; Resonance; Waves; Angular Momentum; Torques and Gyroscopes; Kepler's Three Laws; The Kepler Problem; Energy and Eccentricity; Navigating in Space; From Kepler to Einstein; Harmony of the Spheres; Beyond The Mechanical Universe; Static Electricity; The Electric Field; Potential and Capacitance; Voltage, Energy and Force; The Electric Battery; Electric Circuits; Magnets; The Magnetic Field; Vector Fields and Hydrodynamics; Electromagnetic Induction; Alternating Currents; Maxwell's Equations; Optics; The Michelson–Morley Experiment; The Lorentz Transformation; Velocity and Time; Mass, Momentum, Energy; Temperature and the Gas Laws; Engine of Nature; Entropy; Low Temperature; The Atom; Particles and Waves; Atoms to Quarks; and The Quantum Mechanical Universe.

[8]The original National Advisory Committee consisted of filmmaker Frank Capra; Dr. John Dowling of Mansfield State College; Dr. Charles Holbrow, Colgate University; Dr. Gerald Holton, Harvard University; Shirley Hufstedler, former Secretary of Education; Dr. Robert Karplus, University of California, Berkeley; Dr. Joseph Krieger, Brooklyn College; Mr. William Layton, Palisades High School; Dr. Frank Oppenheimer, director of *The Exploratorium*, San Francisco; and David Ridgway, Lawrence Hall of Science, Berkeley. During the course of the project, Professor Holton withdrew from the committee and Dr. Oppenheimer passed away. Dr. Karplus was prevented by illness from ever participating.

[9]The local advisory committee, chaired by Olenick, met five or six times each year, contributing invaluable criticism of drafts of textbook chapters and scripts. The members were Dr. Ronald Brown, California Polytechnic State University, San Luis Obispo; Dr. Elizabeth Hodes, Santa Barbara City College; Keith Miller, Pasadena City College; Dr. Eldred Tubbs, JPL, Caltech; Dr. Eric Woodbury, Hughes Aircraft Co., retired.

[10]The JPL computer Graphics Lab was headed by Robert Holzman, who paved the way administratively for Blinn to work on TMU.

[11]J. F. Blinn, *The Mechanical Universe: An Integrated View of a Large Scale Animation Project* (Pasadena, 1987), unpublished.

[12]The same derivations are presented in the textbooks, Ref. 1, where they can be studied at leisure.

[13]See, for example, R. E. Yager, Technical Report #21, Science Education Center, University of Iowa (1980).

[14]Don Barron, Wheaton High School, Wheaton, MD; Judith Healy, Plano Senior High School, Plano, TX; Charles Lang, Omaha Westside High School, Omaha, NB; William Layton, Palisades High School, Pacific Palisades, CA; William Leader, Loara High School, Anaheim, CA; Franceline Leary, Troy High School, Troy, NY; Don Martin, Cistercian Preparatory School, Irving, TX; Katherine Mays, Bay City High School, Bay City, TX; Fred Oswald, Napa High School, Napa, CA; Donald Sparks, North Hollywood High School, North Hollywood, CA; George Taylor, Jr. The Baylor School, Chattanooga, TN; and Courtney Willis, University High School, Greeley, CO. In 1986 Debra Cannon, Grand Prairie High School, Grand Prairie, TX, joined the group.

[15]Evaluation was conducted by Geraldine Grant and J. Richard Harsh, Educational Evaluation Consultants, Long Beach, CA.

[16]The high-school materials are distributed in "Quads." Each Quad consists of four 15-min video adaptations and related print materials, both for the student and the teacher.

(1) QUAD I: Newton's Laws; The Apple and the Moon; Harmonic Motion; and Navigating in Space.

(2) QUAD II: Conservation of Energy; Conservation of Momentum; Angular Momentum; and The Fundamental Forces.

(3) QUAD III: The Law of Falling Bodies; Inertia; Moving in Circles; and The Millikan Experiment.

(4) QUAD IV: Kepler's Laws; Introduction to Waves; Temperature and the Gas Laws; Curved Space and Black Holes.

(5) QUAD V: Electric Fields and Forces; Potential Difference and Capacitance; Equipotentials and Fields; Simple dc Circuits.

(6) QUAD VI: Magnetic Fields; Electromagnetic Induction; Alternating Current; The Michelson–Morley Experiment.

Currently under development are four more modules on modern physics and an overview program about the entire series. See Ref. 3 for the address of the distributor.

[17]Reports of three of these efforts have been published in *The Mechanical Universe and Beyond Newsletter* 1 (2), Fall 1987.

[18]Awards include: American Film Festival (Honorable Mention); Birmingham International Film Festival (Gold); Chicago International Film Festival (Gold); Houston International Film Festival (Gold); International Film and TV Festival (Gold); National Educational Film Festival (Gold); and International Science Film Festival (Leningrad) (First). At the prestigious Cindy Awards in Los Angeles, The Mechanical Universe won a Gold, Best of Show Nomination, Videography Award, Directing Award, and a Writing Award.

Noted added in proof: In November 1987, The Lorentz Transformation, an episode from Beyond the Mechanical Universe, was awarded The Japan Prize for Television, the world's most coveted award for educational material.